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MULTIPLE CALCRETE PROFILES IN THE TABERNAS BASIN, SOUTHEAST SPAIN: THEIR ORIGINS AND GEOMORPHIC IMPLICATIONS

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ABSTRACT

This paper describes a sequence of Pliocene(?) to Quaternary age calcretes developed within alluvial fan and fluvial gravels in the Tabernas Basin, Almería Province, southeast Spain. Calcrete profiles are described from sites adjacent to major tributaries of the Rambla de Tabernas. Six distinct calcrete units are identified within the basin. These have variable distributions but have developed in an identifiable evolutionary sequence. Two pairs of calcrete units are widely present across the basin preserving two former land surfaces. Each of the former land surfaces has been planated and subsequently buried by alluvial fan or fluvial gravels. A massive calcrete unit is present at the base of each gravel sequence, immediately in contact with the underlying bedrock, with a less well developed calcrete unit situated at the top of the gravel sequence. The lowest two calcrete units within the basin are more spatially restricted and are confined to the floors and flanks of incised drainage lines.

The geochemistry, macro- and micromorphological properties and geomorphological positions of the calcrete units are outlined and, on the basis of this information, their mode of origin identified. Two main modes of calcrete genesis appear to be present: massive calcretes situated in direct contact with bedrock are suggested to have formed by groundwater processes, whilst calcretes situated at the top of gravel sequences are likely to have developed by pedogenic processes. Calcrete genesis is subsequently considered in the context of the reconstruction of the early phases of landscape development, and is suggested to have been controlled by phases of uplift and stability within the Tabernas Basin. © 1998 John Wiley & Sons, Ltd.

KEY WORDS: calcrete; southeast Spain; Tabernas Basin, pedogenesis; groundwater calcretization

INTRODUCTION

Alluvial fans at mountain fronts are important components of the landscape of semi-arid southeast Spain and show a complex history of aggradation and dissection associated with regional tectonic activity and climatic change (e.g. Harvey, 1978, 1984a,b, 1987a,b, 1988, 1990, 1996, 1997). The component surfaces of many fans exhibit varying degrees of calcrete development, and in places these calcretes are sufficiently indurated to stabilize fan surfaces and have a major impact upon the connectivity of the mountain fluvial system (Harvey, 1984b, 1987a, 1996).

This paper describes a complex suite of Plio-Pleistocene calcretes which developed in alluvial fan and fluvial gravels in the Tabernas Basin, Almería Province, Spain. Representative profiles are described from sites adjacent to the Rambla del Búho and the Rambla de Reinelo Ibáñez, both tributaries of the Rambla de Tabernas. The geochemistry, macro- and micromorphological properties and geomorphological positions of the different calcrete units are discussed, and, on the basis of this information, their mode of origin suggested. Calcrete genesis is subsequently considered in the context of the reconstruction of the early phases of landscape development within the Tabernas Basin.

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GEOLOGY, LANDFORMS AND TECTONIC SETTING OF THE TABERNAS BASIN

The Tabernas Basin is located in an area with a mean annual precipitation of 245 mm per year (Eliaz and Ruiz, 1977). The basin is bounded by the Betic Sierra de los Filabres to the north, the Sierra Alhamilla to the south, and the Sorbas Basin to the east. The mountain ranges to the north and south are dominated by Precambrian to Triassic mica schists and other high-grade metamorphic rocks of the Nevado–Filabrides complex (Figure 1). These metamorphic rocks are partly overlain in the northern Sierra Alhamilla by nappes of Palaeozoic to Triassic low-grade metamorphic and Triassic sedimentary rocks of the Alpujarrides complex (Weijermars *et al*., 1985).

The development of the Tabernas Basin relates to movements of the African and European plates between the Jurassic and Miocene and to subsequent neotectonic activity. Marine basin sedimentation began following Miocene uplift of the Sierra de los Filabres and later uplift of the Sierra Alhamilla. The earliest deposits within the basin (Figure 2) are pre-Tortonian conglomerates which are overlain by sequences of Tortonian and Messinian marls, turbidites, conglomerates, marine-mud and sandstone laminites (Weijermars *et al*., 1985). The basin underwent transgression and subsequent regression and erosion during the Pliocene, culminating in the deposition of continental barranco-type river deposits and debris flows across the entire Tabernas Basin (Postma, 1984a,b). The oldest calcretes described in this paper have developed in similar or younger alluvial fan or fluvial gravels deposited on top of Tortonian marls, but their equivalence to the calcrete shown at the base of the alluvial gravels in Figure 2 is not yet established.

The Neogene sedimentary sequence contains a number of major unconformities indicating ongoing tectonism during the course of basin infilling (Weijermars *et al*., 1985). Movement along strike-slip and related mountain front reverse fault systems has occurred since the Pliocene. This has disturbed Quaternary sediments and strongly influenced landform development, as has been reported in studies of regional drainage patterns in the adjacent Sorbas Basin (e.g. Harvey and Wells, 1987; Harvey *et al*., 1995; Mather and Harvey, 1995) and in studies of alluvial fan development (Harvey, 1987a). In the Tabernas area, the greatest effects of tectonic disturbances upon landform development have occurred along the northern margin of the Sierra Alhamilla resulting in, for example, dissection of isolated alluvial fans (Harvey, 1996). However, the geomorphology has also been strongly influenced by uplift in the eastern part of the Tabernas Basin, as evidenced by the fact that the oldest basin fill rocks (early Tortonian conglomerates) occur at their highest elevation in this area (Harvey, pers. comm.). This has resulted in considerable incision and the development of steep regional gradients, with the incised Tabernas drainage falling 260 m in less than 16 km from Tabernas town to the Andarax River. As a result, the local dissected relief within the basin is in excess of 200 m (Harvey, 1987a), with maximum relief at the western margin of the study area.

METHODOLOGY

Calcrete properties were examined in profiles from two representative areas on opposite sides of the Tabernas Basin (Figure 3). These were the extensive exposures along the Rambla del Búho to the northwest of Tabernas (Figure 4) and those in the vicinity of the Rambla de Reinelo Ibáñez immediately south and southwest of the town. Precise locations of all sample profiles are given in Tables I and II. Profiles N1 to N6 were located to the north of the Rambla de Tabernas with profiles S1 to S6b situated to the south of the rambla.

At each site, calcrete profiles were logged and sampled, with calcrete colour determined using a Munsell Soil Colour chart. Petrographic and geochemical analyses were carried out on subsamples. Petrographic thin sections of subsamples from each profile were analysed using a binocular microscope, with point counts made to quantify the percentage of host grains, carbonate cement and void space. Bulk chemical composition of the remaining half of each sample was determined by X-ray fluorescence spectrometry (XRF). In addition, two representative samples of uncemented alluvial fan gravel were analysed by XRF. XRF analysis was undertaken by the lithium tetraborate fused disc method using a Philips PW 1400 X-Ray Spectrometer, with loss on ignition determined at 1000°C.

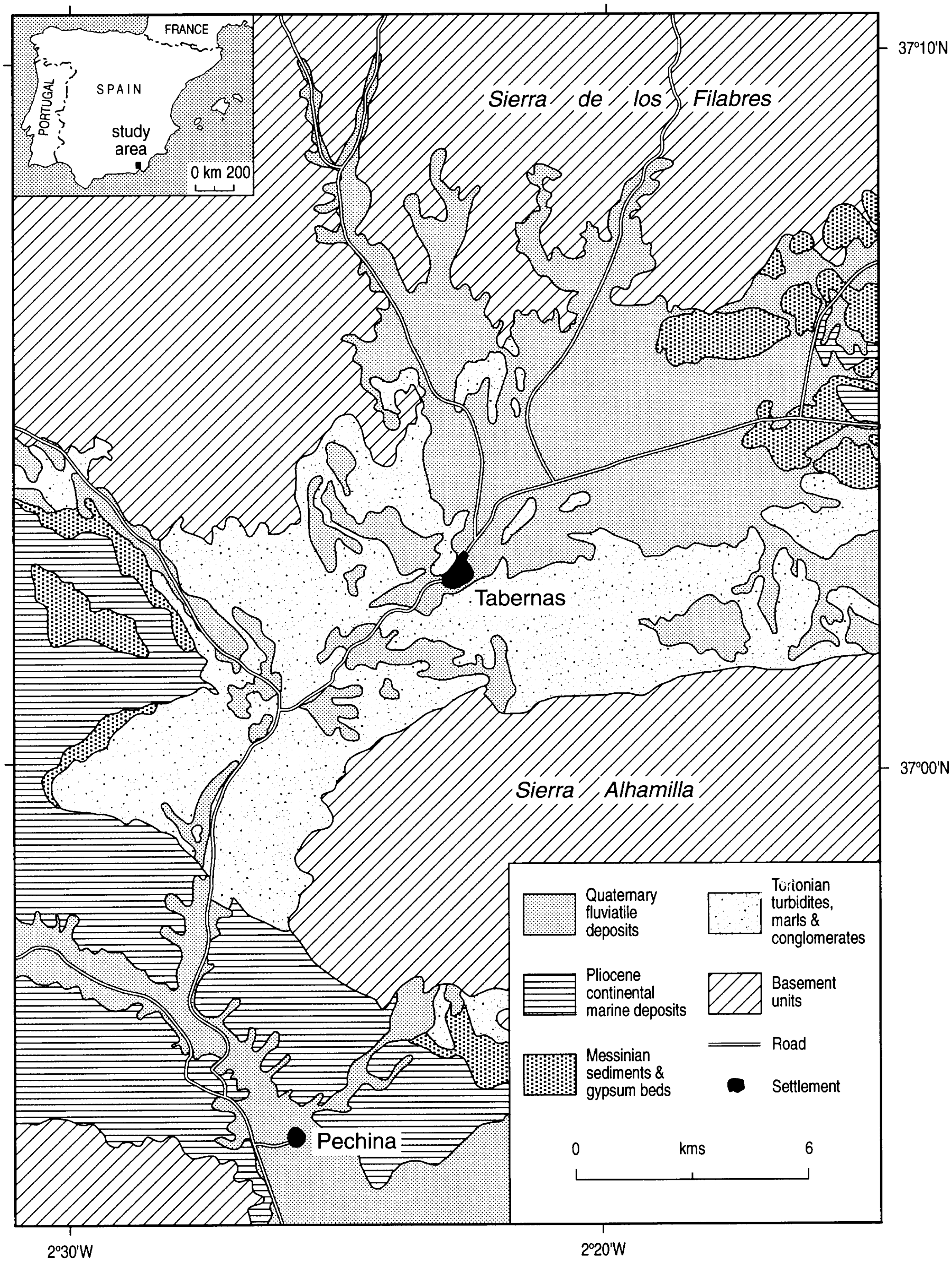

Figure 1. Simplified geological map of the Tabernas Basin (after Weijermars *et al*., 1985)

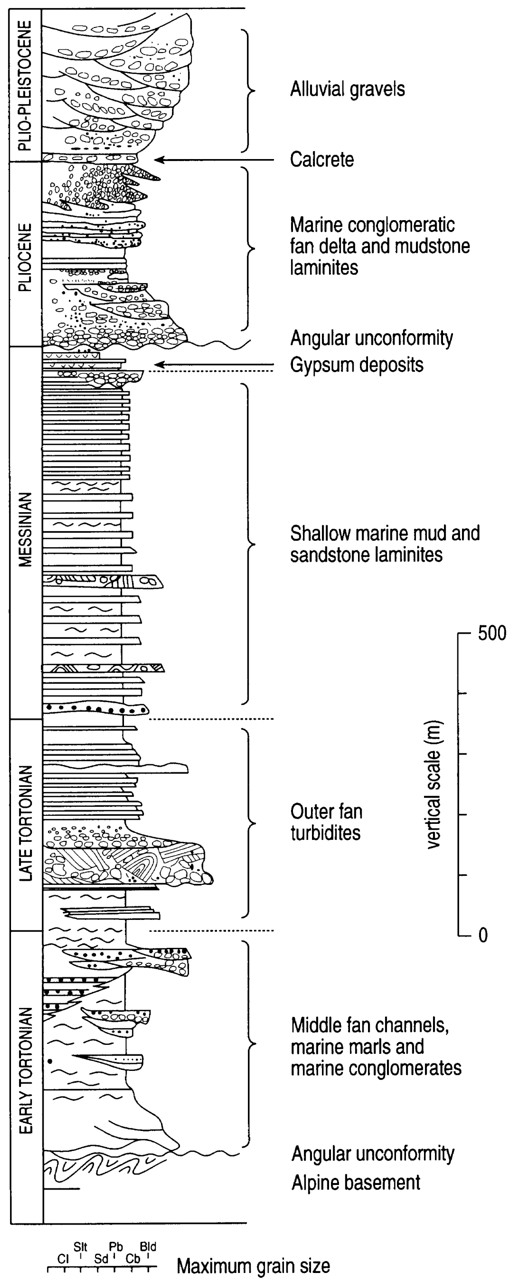

Figure 2. Composite stratigraphic column of the Almería and Tabernas Basins (after Weijermars *et al.*, 1985), showing the full sequence of post-Alpine basement sediments culminating in the deposition of barranco-type gravels. Note that the calcretes described in this paper are developed upon bedrock representing the Tortonian section of this sequence

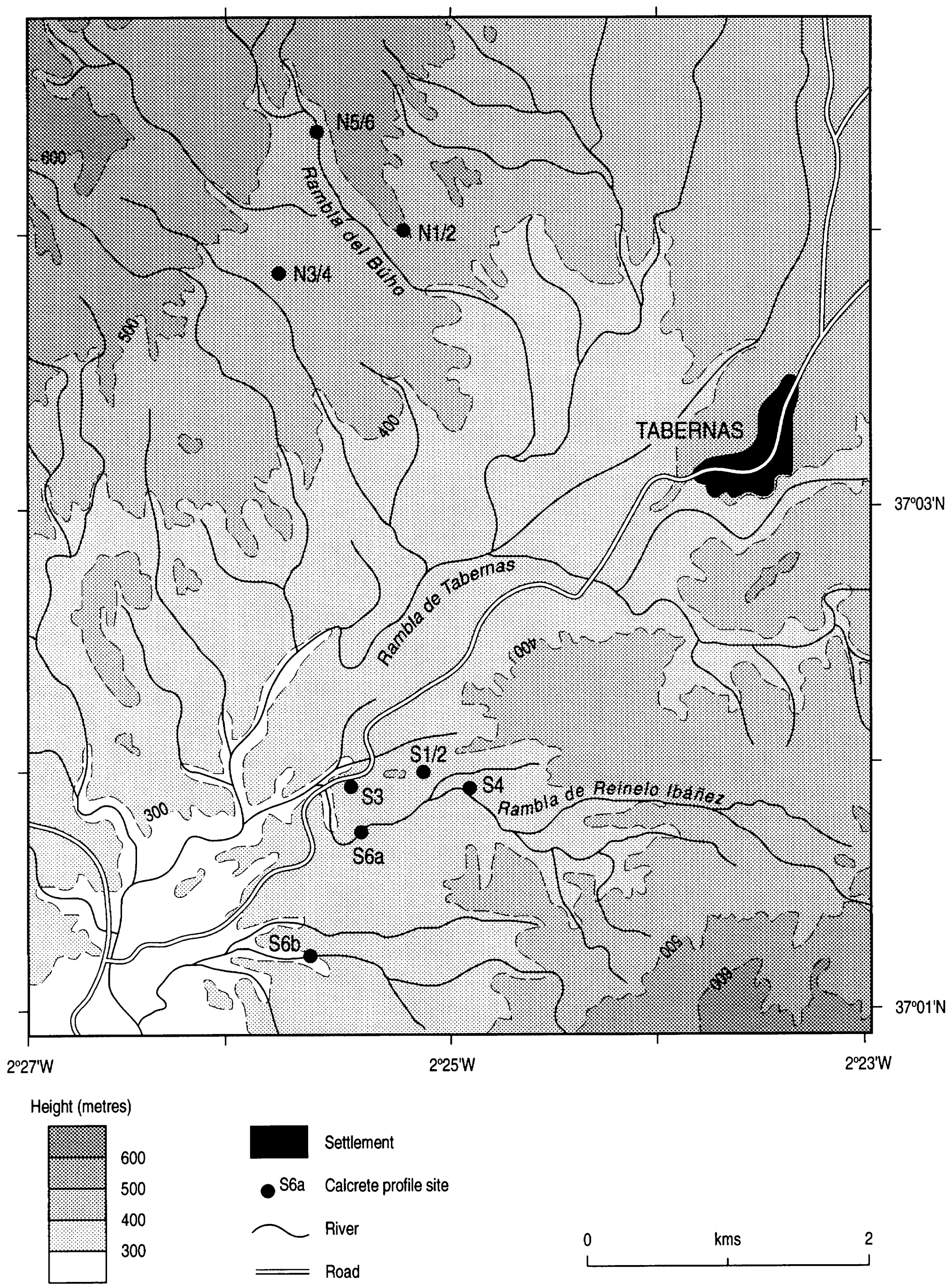

Figure 3. Locations of calcrete profiles within the Tabernas Basin

Figure 4. View of calcrete units in the Tabernas Basin, looking southeast across the basin from sample site N3/4. The major planated surface on the right of view is capped by alluvial fan or fluvial sands and gravels cemented by calcrete units N3 and N4, whilst the high land on the left of view is capped by calcrete units N1 and N2, creating a stepped profile

GEOMORPHOLOGICAL SETTINGS OF CALCRETE PROFILES

Six calcrete units have been identified within the Tabernas Basin. These have variable distributions but appear to occur in two distinct geomorphological settings: either as indurated units preserving former land surfaces or as more spatially confined units restricted to the floors and flanks of incised drainage lines. These relationships are shown schematically in Figure 5.

The uppermost four calcrete horizons (Figure 5) are widely present across the basin, and preserve two flat to undulating palaeosurfaces. The four calcrete units occur as two pairs. In each pair, the lower calcrete is situated directly upon bedrock and is separated from the overlying calcrete by a variable thickness of alluvial fan or fluvial gravels. The lower unit of each pair of calcretes has an abrupt boundary with the underlying bedrock, whilst the upper unit has a more diffuse lower boundary. The two pairs of calcretes form two distinct plateau surfaces across the Tabernas Basin which slope towards the present course of the Rambla de Tabernas.

The lowest two calcrete units within the basin are more spatially restricted and tend to be located either within, or immediately adjacent to, incised drainage lines (Figure 5). These calcrete units either preserve minor alluvial fans or cement sedimentary fills within drainage lines. In areas where fluvial incision has occurred following calcretization, the channel-marginal calcrete units are frequently exposed within channel floors and flanks, and may inhibit further downcutting leading to the development of waterfalls within river courses.

PROPERTIES OF CALCRETE PROFILES

The profile characteristics (Tables I and II), micromorphological properties (Tables III and IV) and geochemistry (Tables V and VI) of each of the six calcrete units will now be described, in order of their landscape position and geomorphological setting.

Properties of calcretes from the upper calcretized palaeosurface

Calcretes N1 and N2 from the Rambla del Búho area and calcretes S1 and S2 from the vicinity of the Rambla de Reinelo Ibáñez represent the two calcrete units from the highest extensive calcretized land surface in the

Table I. Characteristics of calcrete profiles from the area surrounding the Rambla del Búho to the northwest of Tabernas

Calcrete profile number	Profile location	Profile code	Profile thickness (m)	Munsell colour range	Profile summary
N2	37° 03.81′N 002° 25.12′W	TAB96/1	2·00	5YR 7/4–10YR 4/2	Developed in upper 2 m of schist and quartz gravels. Indurated surface, decreasing in hardness below.
N1	37° 03.81′N 002° 25.12′ W	TAB96/2	2·70	10YR 5/1–2.5Y 5/4	Formed in quartz and schist gravels. Hard upper surface with continuous cementation below.
N4	37° 03.91′N 002° 25.68′W	TAB96/3	0·40	7.5YR 5/4	Weakly developed. Discontinuous nodules at a depth of 30–45 cm in soil profile over weathered schist gravel.
N3	37° 03.91′N 002° 25.68′W	TAB96/4	3·40	2.5Y 5/1–2.5Y 4/2	Massive calcrete forming extensive crust. Formed in bedded gravels. Little profile variability.
N5	37° 04.30′N 002° 25.62′W	TAB96/5	1·50	2.5Y 5/1–5Y 4/1	Formed in thin alluvial fan over bedrock. Generally grey but some iron staining associated with groundwater.
N6	37° 04.38′N 002° 25.58′W	TAB96/6	1·20–2·00	2.5Y 6/2	Uniform brownish grey calcrete in alluvial gravel over rock.

Table II. Characteristics of calcrete profiles from the area surrounding the Rambla de Reinelo Ibáñez

Calcrete profile number	Profile location	Profile code	Profile thickness (m)	Munsell colour range	Profile summary
S2	37° 01.95′N 002° 25.20′W	TAB96/8	2·00	10YR 5/6–2.5Y 4/1	Developed in 8–10 m gravels. Indurated in upper 70–80 cm. Weak, columnar cementation below to 2 m.
S1	37° 02.05′N 002° 25.21′W	TAB96/7	3·10	7.5YR 5/8–5Y 2/2	Massive, hard, strongly cemented, developed in coarse gravels. Upper 40 cm weathered. Abrupt bedrock contact.
S4	37° 01·76′N 002° 25.03′W	TAB96/10	1·50	10YR 6/4	Weak calcretization of top 1·5 m of 5·5 m of gravels. Poorly cemented throughout the profile.
S3	37° 01.83′N 002° 25.31′W	TAB96/9	3·00	10YR 4/6–10YR 4/2	Uniform, massive, strongly cemented calcrete in gravels of variable lithology.
S6a	37° 01.91′N 002° 25.39′W	TAB96/11	1·40	10YR 3/2	Strongly cemented calcrete within bedrock channel. Abrupt contact with bedrock at base and sides of channel.
S6b	37° 01.16′N 002° 25.60′W	TAB96/12	3·50	10YR 4/2–2.5Y 4/1	Strongly cemented with weathered upper surface. Abrupt contact with bedrock channel.

Tabernas Basin. This surface is best preserved to the southwest of Tabernas town but also occurs on hilltops to the north and west of the town.

Calcrete profiles N1 (profile TAB 96/2; Figure 6) and S1 (Profile TAB 96/7) rest directly upon marine sedimentary bedrock, and exhibit an abrupt and unconformable contact with the underlying bedrock. Both profiles consists of approximately 3 m of calcrete comprising schist, quartzite, quartz and sandstone gravels (with some clasts >40 cm length) cemented mostly by calcium carbonate. In general, the host sediments within profiles to the north of the Rambla de Tabernas are dominated by quartz and schist clasts, whilst those to the south additionally contain quartzite and sandstone gravels. Both profiles are hard, massive, densely cemented and relatively uniform, although some weathering is evident in the upper 40 cm of profile S1. Both profiles have a relatively smooth upper surface which is coated by a laminar calcrete layer of variable thickness (typically 5 to 10 mm). There is some secondary cementation evident in both profiles, with carbonate deposited in void spaces in profile S1 and in secondary cracks in N1. Although some displacement of grains during the process of calcretization is apparent, there is no evidence of a significant break in sedimentation between the gravels incorporated within the calcrete units and those overlying them, suggesting that the calcrete developed near the base of a thick gravel sequence. Hues range from 10YR in the upper parts of profile N1 to 2.5Y towards its base,

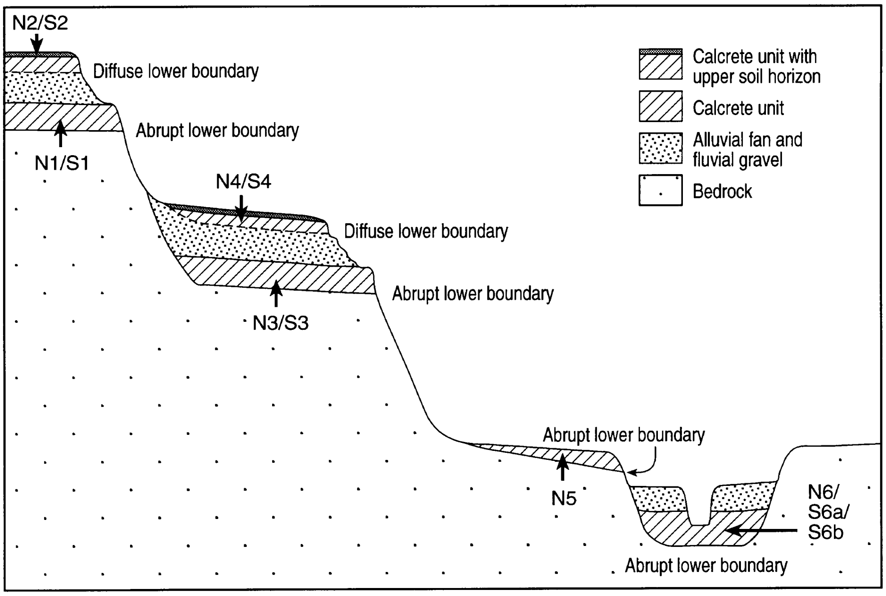

Figure 5. Schematic diagram of calcrete relationships within the Tabernas Basin

Table III. Micromorphological properties of calcrete profiles from the Rambla del Búho area

Calcrete profile number	Profile code	Calcrete host material	Calcrete matrix characteristics
N2	TAB96/1	Schist and quartzite with some quartz and biotite.	Cement dominated by micritic calcite with some patches of microsparite present. Some glaebules present with concentric growth structures. Glaebules coalesce in upper parts of the profile. Host particles are rarely in contact with one another.
N1	TAB96/2	Schist and quartzite plus biotite, quartz and minor opaques.	Highly variable cement. Uppermost 120 cm and basal 40 cm of the profile are dominated by a microsparite cement, with crystal size increasing towards host grains. Some localized micrite present. Cements at the centre of the profile are dominated by an interlocking mosaic of sparite crystals with only minor micrite. Host particles are rarely in contact with one another.
N4	TAB96/3	Schist and quartzite plus minor opaques.	Densely cemented by micritic calcite. Some glaebules present with concentric growth structures. Host particles are rarely in contact with one another.
N3	TAB96/4	Schist and quartzite with quartz and minor opaques.	Cement is dominated by an interlocking mosaic of sparite crystals with minor amounts of micritic and microsparite calcite present. Calcite crystals tend to increase in size towards the centres of either completely or partially infilled voids. Cement is relatively uniform throughout the profile, although more micritic calcite is present in uppermost and the lowest 40 cm of the profile. Host particles are rarely in contact with one another.
N5	TAB96/5	Quartzite and schist with mica, quartz and minor opaques.	Densely cemented by a combination of micrite and microsparite, with micrite mostly adjacent to host grains and calcite crystals occupying infilled voids. The calcrete profile exhibits little variability except in uppermost sections where some glaebular structures are present. Host particles are rarely in contact with one another.
N6	TAB96/6	Schist with minor quartzite and biotite.	Cement is dominated by interlocking sparite crystals which are optically continuous in the upper sections of the profile. Localized patches of micritic calcite are also present. Multiple stage void linings are present, particularly in lower sections of the profile, where iron oxide is overlain by micritic calcite with further iron oxide infilling void spaces.

Table IV. Micromorphological properties of calcrete profiles from the Rambla de Reinelo Ibáñez area

Calcrete profile number	Profile code	Calcrete host material	Calcrete matrix characteristics
S2	TAB96/8	Quatzite, with lesser quartz and opaque minerals.	Cement dominated by micrite with sparite present closer to partially or completely infilled voids. Calcrete structure varies from a simple micritic cement to areas with glaebular structures cemented by micrite. Host particles are rarely in contact with one another.
S1	TAB96/7	Quartzite, with lesser schist, biotite and quartz.	Uppermost sections of the profile are cemented by micritic calcite which appears to have simply infilled void space between host grains. The calcrete cement shows a variety of structures from a depth of 50 cm downwards. Some grains are coated with micrite, with void walls lined with concentric layers of calcite. Where voids are not completely infilled with layered calcite, a mosaic of interlocking calcite crystals fills remaining void spaces. Host particles are rarely in contact with one another.
S4	TAB96/10	Schist, with sandstone fragments and opaques.	Cement dominated by fine-grained micrite, which coats host grains and encompasses some calcite glaebules. The centres of some voids are filled with microsparite.
S3	TAB96/9	Quartzite, sandstone and calcrete fragments with lesser schist, quartz and diatoms.	Cement is highly variable but appears to be dominated by either micrite or microsparite. Micrite most commonly occurs as a grain coating and has a well developed layered structure in places. Microsparite occurs away from grains and also as a void infill. Interlocking sparite crystals occur at the centre of some former voids. Host particles are rarely in contact.
S6a	TAB96/11	Quartzite and schist with minor calcrete and sandstone.	Upper parts of the profile contain a relatively simple micritic to microsparite cement which appears to have simply infilled intergranular voids rather than precipitating as a grain coating cement. Lower sections of the profile exhibit a more complex cement with micrite occurring in confined intergranular spaces and radial calcite lining the walls of larger void spaces. Many voids are infilled with interlocking sparite near their centres. Host particles are rarely in contact with one another.
S6b	TAB96/12	Quartzite and schist with minor quartz	Complex cement comprising micritic calcite close to grains with microsparite in larger void spaces. The centres of many former voids are filled with an interlocking mosaic of sparite. The percentage of micrite to microsparite is highly variable within the section, but both cement types occur throughout the profile. Host particles are rarely in contact with one another.

and between 5Y and 7.5Y in profile S1, with weathering indicated by strong brown colouration (7.5YR 5/8) at the surface.

In thin section, both profiles comprise gravels cemented by microcrystalline calcite cement in their uppermost sections, which is replaced by an interlocking mosaic of sparite crystals with only minor amounts of micrite in the centre and lower sections of each profile (Figure 7). Many void spaces within profiles are lined by concentric layers of micrite, suggesting calcite precipitation in association with percolating porewaters. The bulk chemistry of profile S1 (Table VI) shows very little variability down the profile, with levels of CaO, SiO_2 Al_2O_3 and Fe_2O_3 remaining relatively constant. Profile N1 shows some variability, most notably a slight decline in the amount of CaO down the profile accompanied by an associated increase in SiO_2. Relatively high levels of MgO are present within the upper sections of the profile, suggesting the occurrence of Mg-rich calcite within the cement.

In contrast, calcrete profiles N2 (Profile TAB 96/2) and S2 (Profile TAB 96/8) do not have an abrupt lower boundary and are developed at the surface of schist- and quartz-rich alluvial fan or fluvial gravels overlying profiles N1 and S1 respectively. These gravels are up to 10 m thick on the north side of the basin and 8 to 10 m thick in the south. Calcrete development is variable, with the upper 2 m of the gravels cemented in profile N2 but only the upper 70 to 80 cm in S2. Both calcretes have indurated upper surfaces but decrease in hardness down-profile, with profile S2 exhibiting a columnar structure reflecting differential cementation. The upper surfaces of both profiles show some reddening (5YR 7/4 in N2 and 10YR 5/6 in S2). In thin section, profiles N2 and S2 are distinctly different from profiles N1 and S1 in that their cement is dominated by micritic calcite and exhibits

Table V. Bulk chemistry and point count data for calcrete samples from the area surrounding the Rambla del Búho (bulk chemical analysis by XRF)

Sample information			Bulk chemical data (% composition)								Point count data (%)		
Calcrete	Sample no.	Depth (cm)	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Other	LOI (%)	Total	Grains	Cement	Voids
N2	TAB96/1/1	5	21·95	4·24	2·51	1·21	37·41	1·47	31·30	100·09	21	79	0
N2	TAB96/1/2	150	49·75	8·22	4·77	1·01	17·41	2·42	15·96	99·54	67	27	6
N1	TAB96/2/1	0	29·11	5·02	3·55	12·19	19·07	1·77	29·00	99·71	30	68	2
N1	TAB96/2/2	100	44·98	7·38	4·01	5·01	16·61	2·24	19·39	99·62	43	57	0
N1	TAB96/2/3	200	47·37	8·81	3·85	3·23	16·45	2·56	17·57	99·84	62	37	1
N1	TAB96/2/4	270	57·62	8·44	5·10	1·36	11·83	2·95	12·21	99·51	27	73	0
N1	TAB96/2/5	275	55·42	11·81	3·70	1·24	11·56	3·40	12·54	99·67	–	–	–
N4	TAB96/3/1	40	47·40	8·24	3·64	0·67	19·62	2·57	17·70	99·84	57	42	2
N3	TAB96/4/1	0	53·37	8·24	3·98	0·74	16·32	2·42	14·68	99·75	51	43	6
N3	TAB96/4/2	100	42·14	7·74	5·08	0·70	22·07	2·37	19·56	99·66	56	44	0
N3	TAB96/4/3	200	52·14	8·88	4·98	0·88	16·12	2·79	14·51	100·57	53	44	3
N3	TAB96/4/4	300	50·41	8·71	5·05	0·67	16·83	2·59	15·36	99·62	57	39	4
N3	TAB96/4/5	330	49·67	10·00	4·61	0·84	16·29	3·14	14·68	99·23	38	61	1
N5	TAB96/5/1	0	12·30	3·03	1·37	0·50	44·43	1·21	36·71	99·55	8	90	2
N5	TAB96/5/2	50	31·87	7·57	4·58	0·78	28·12	2·63	24·88	100·43	35	61	3
N5	TAB96/5/3	100	43·00	8·31	5·07	0·77	20·97	3·00	18·68	99·80	40	58	3
N5	TAB96/5/4	130	35·33	7·64	5·61	0·96	25·04	2·46	22·05	99·09	34	65	1
N6	TAB96/6/1	0	53·43	10·26	4·31	0·90	13·93	2·93	14·73	100·49	68	32	0
N6	TAB96/6/2	50	50·63	9·56	4·02	1·09	16·37	2·60	15·28	99·55	64	35	1
N6	TAB96/6/3	120	46·18	8·95	3·31	1·20	19·87	2·18	17·66	99·35	64	36	0

Table VI. Bulk chemistry and point count data for calcrete samples from the area surrounding the Rambla de Reinelo Ibáñez (bulk chemical analysis by XRF)

Sample information			Bulk chemical data (% composition)								Point count data (%)		
Calcrete	Sample no.	Depth (cm)	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Other	LOI (%)	Total	Grains	Cement	Voids
S2	TAB96/8/1	0	52·09	6·49	3·67	0·67	18·53	2·15	16·61	100·21	49	51	0
S2	TAB96/8/2	50	59·32	8·75	4·01	1·11	11·98	2·72	12·44	100·33	49	48	3
S1	TAB96/7/1	0	61·24	9·50	7·20	0·87	8·44	2·67	9·73	99·65	45	54	1
S1	TAB96/7/2	40	63·67	8·60	5·35	0·73	8·72	2·18	10·15	99·40	61	34	5
S1	TAB96/7/3	100	67·86	10·84	5·90	1·16	4·42	2·99	6·50	99·67	56	44	0
S1	TAB96/7/4	200	65·25	9·79	5·59	0·96	6·60	2·83	8·88	99·90	53	41	6
S1	TAB96/7/5	310	64·70	9·13	4·41	1·01	8·26	2·80	9·43	99·74	55	45	0
S4	TAB96/10/1	5	56·00	8·27	5·01	1·17	13·10	2·29	13·44	99·28	42	57	1
S3	TAB96/9/1	0	28·53	3·82	2·68	5·27	29·18	1·57	29·10	100·15	39	58	3
S3	TAB96/9/2	50	39·71	5·69	2·87	1·25	23·72	2·49	22·35	98·08	50	48	2
S3	TAB96/9/3	100	45·58	5·32	3·98	1·59	21·60	1·85	19·96	99·88	48	51	1
S3	TAB96/9/4	200	39·35	6·04	3·58	1·84	24·66	2·18	22·47	100·12	55	44	1
S3	TAB96/9/5	250	39·93	5·84	3·54	2·06	23·88	1·99	22·36	99·60	23	73	4
S6a	TAB96/11/1	0	58·87	12·92	5·30	1·31	7·87	3·39	10·21	99·87	55	40	5
S6a	TAB96/11/2	100	53·63	9·50	4·59	1·43	13·90	2·60	14·75	100·40	57	41	2
S6b	TAB96/12/1	0	42·37	8·46	5·01	2·28	19·26	2·32	19·47	99·17	38	55	7
S6b	TAB96/12/2	100	46·70	9·08	4·40	2·33	16·75	2·49	18·03	99·78	48	48	4
S6b	TAB96/12/3	220	44·86	8·18	3·99	1·50	20·20	2·39	19·45	100·57	39	60	1

glaebular or nodular structures with evidence of concentric calcite deposition around host grains (Figure 8). The bulk chemistry of the profiles also differs markedly, with a strong decline in CaO down both profiles and an associated increase in SiO_2, Al_2O_3 and Fe_2O_3 content (Tables V and VI). The decrease in the degree of cementation down the profile is reflected in an increase in percentage pore space.

Figure 6. Profile N1, resting in direct contact with underlying Neogene bedrock (hammer is 30 cm long)

Properties of calcretes from the lower calcretized palaeosurface

Calcretes N3, N4, S3 and S4 are from the next lowest calcretized surface within the Tabernas Basin (Figure 5). This surface is most extensive on the north side of the basin, but is more restricted to the south of the Rambla de Tabernas.

Calcretes N3 (Profile TAB 96/4) and S3 (TAB 96/9) occupy a similar landscape position to profiles N1 and S1 described above, both being located in direct contact with bedrock and buried by a veneer of alluvial fan gravels within which calcretes N4 and S4 have developed (Figure 9). Both N3 and S3 calcretes are well developed, averaging between 3 and 3·5 m in thickness, although some sections within the Rambla del Búho area reach over 5 m in thickness where gravels have infilled former channels cut into the bedrock and have been subsequently calcretized. Inherited sedimentary structures are evident in profile N3 where calcrete has developed within bedded fluvial gravels. Again, the calcretes are hard, massive, uniform, well cemented, slightly weathered in their uppermost sections, and have a laminar layer of 5 to 15 mm thickness on their upper surfaces. Both contain clasts of schist, quartz, quartzite and sandstone, with particles of detrital calcrete additionally present within profile S3. As in the case of calcretes N1 and S1, there does not appear to be any significant difference in particle size between the gravels incorporated within the calcrete and those within the overlying uncemented material. Hues in profile S3 are typically 10YR, greyish or yellowish brown, with 2.5Y hues (greyish brown) extending throughout profile N3.

In thin section, calcretes N3 and S3 are more variable than profiles N1 and S1 described above (Figure 10). The cement in calcrete N3 is dominated by interlocking crystals of sparite with limited amounts of microcrystalline calcite present, although the amount of microcrystalline cement increases towards the top and bottom of the profile. S3 is mainly cemented by fine crystalline calcite, commonly exhibiting concentric layering around the margin of voids, with sparite only present at the centre of void fills. Bulk chemical analysis of samples from profiles N3 and S3 indicates that there is relatively little variability within the two calcretes (Tables V and VI).

Calcrete profiles N4 (TAB 96/3) and S4 (TAB 96/10) are both comparatively weakly developed. In a similar manner to profiles N2 and S2 described above, they are located in the upper sections of fluvial gravels which overlie a basal calcrete unit, in this case calcretes N3 and S3. Calcrete N4 is developed in the uppermost section of 3 m of sediments overlying calcrete N3 and is restricted to a layer of discontinuous nodules at a depth of 30–45 cm in a soil profile overlying weathered schist gravel. Calcrete S4 is also weakly developed and is situated in

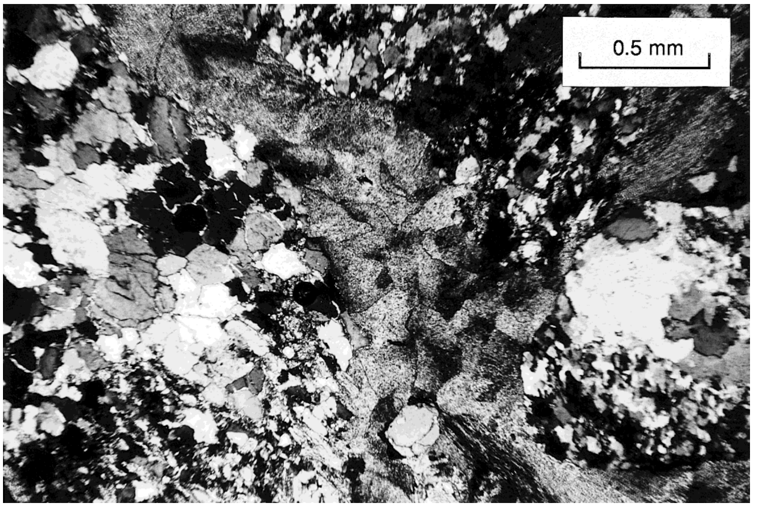

Figure 7. Petrographic thin section of calcrete sample TAB 96/7/5 from Profile S1, showing quartzite and schist fragments cemented by sparite (cross-polarized light)

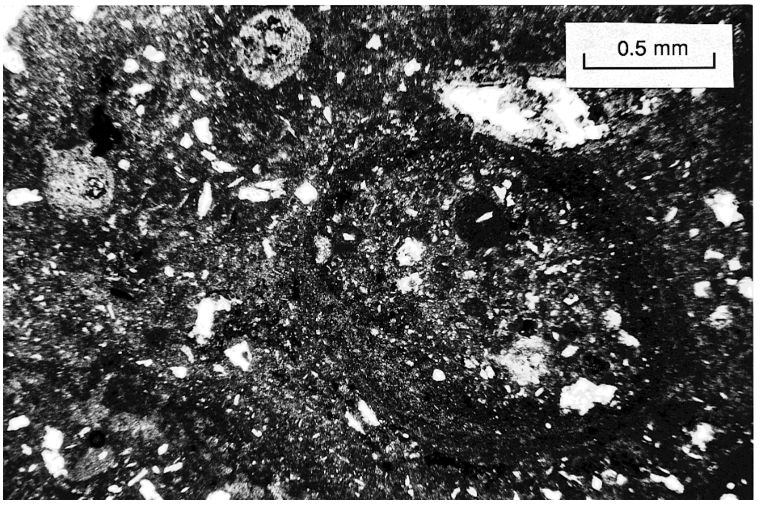

Figure 8. Petrographic thin section of calcrete sample TAB 96/1/1 from Profile N2, showing silt-sized quartz particles cemented by micrite. Numerous glaebular structures and void spaces are visible (cross-polarized light)

the upper section of 5·5 m of fluvial sediments overlying S3. Calcretization of the upper 1·5 m of the gravels has taken place but cementation is poor. A feature of both profiles N4 and S4 is that the degree of cementation and induration of the calcrete declines with depth. The typical colour of both calcretes is 10YR 6/4 (light yellowish brown). Thin section analysis of both profiles N4 and S4 indicates that they have similar cements to profiles N2 and S2, being dominated by micritic calcite and exhibiting glaebular or nodular structures and concentric growth fabrics (Figure 11). Given the limited development of each profiles, only one sample was analysed by XRF making it impossible to identify trends in calcrete geochemistry.

Properties of calcretes exposed in valley flanks and floors

The remaining calcretes exposed within the Tabernas Basin are typically restricted in occurrence and tend to be located within or adjacent to incised drainage features. Calcretes N6 (Profile TAB 96/6), S6a (TAB 96/11) and S6b (TAB 96/12) all occur in the floors and banks of drainage lines (Figure 12). The calcretes have developed within quartz- and schist-rich gravels and are hard, massive and well indurated. The gravels represent sedimentary infills in the floors of incised bedrock channels and are completely calcretized so that the calcrete is in abrupt contact with the underlying rock. The majority of outcrops exposed in stream beds are 1·2 to

Figure 9. Profiles N3 and N4 adjacent to the Rambla del Búho. Roger Smith is standing on top of calcrete N3, which is overlain by gravel and capped by calcrete N4

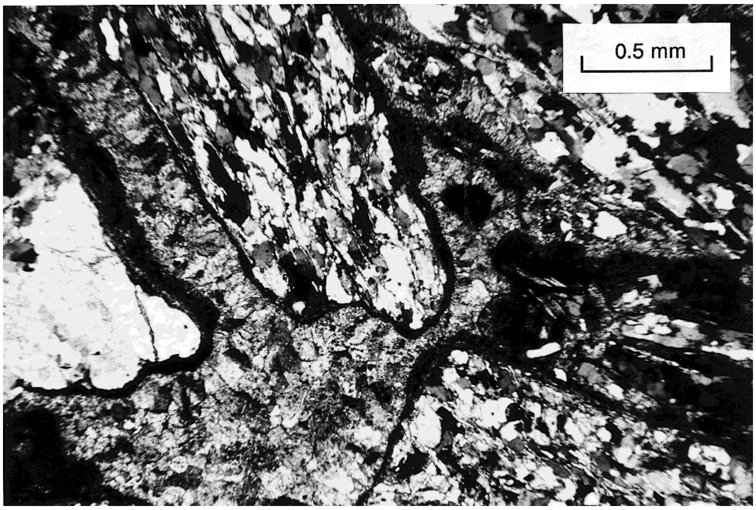

Figure 10. Petrographic thin section of calcrete sample TAB 96/4/4 from Profile N3, showing quartzite and schist fragments cemented by sparite (cross-polarized light)

1·4 m thick to the basal contact with bedrock, but many calcretes are thicker in places, up to 2 m in the case of N6. This variation in calcrete thickness appears to reflect variability in the thickness of the gravel within which the calcrete developed. Where the outcrop is in a river bed, erosion of the upper calcrete surface may have taken place, reducing the apparent thickness of the calcrete. Most calcretes appear uniform in colour and are brownish grey (2.5Y 6/2) to greyish brown (10YR 3/2) throughout. Profile S6a is overlain unconformably by 2 to 3 m of weakly cemented gravels. The extent to which other valley floor calcretes may also have been buried by gravel is unknown, as fluvial activity within the incised channels is likely to have removed any sediment.

In thin section, calcretes N6, S6a and S6b exhibit fabrics which are most closely similar to those identified in profiles N1, S1, N3 and S3 (Figure 13). Calcrete N6 is cemented by interlocking optically continuous sparite crystals, with a similar appearance to calcretes N1 and N3. Profiles S6a and S6b have more variable cements with a mixture of micrite and microcrystalline calcite occurring throughout both calcretes, micrite lining void

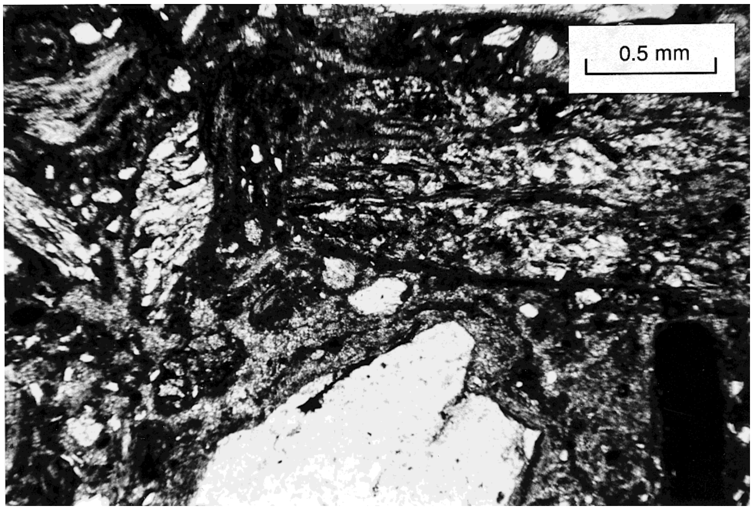

Figure 11. Petrographic thin section of calcrete sample TAB 96/10/1 from Profile S4, showing quartz, quartzite and schist fragments cemented by micritic calcite. Micrite is generally present as a grain coating, with the calcrete containing many voids. Minor glaebular structures are visible, but these are poorly developed (cross-polarized light)

Figure 12. Profile S6b where it forms a waterfall in a southern tributary of the Rambla de Tabernas

walls and sparite filling void spaces, similar to profiles S1 and S3. Bulk chemical analysis indicates very little variability within any of the calcrete profiles (Tables V and VI).

Calcrete N5 (Profile TAB 96/5) is developed within a thin veneer of completely cemented alluvial fan or fluvial gravels on the western side of the Rambla del Búho. The calcretized gravels are hard, well cemented, up to 1·5 m thick, and sit directly upon bedrock with an abrupt contact. Weak calcretization of the underlying bedrock is evident in places. The calcrete is generally grey in colour (5Y 5/1) but some sections are strongly iron stained, reflecting either the occurrence of pyrite within the graphite-schist parent material or colouration from overlying red soils.

This profile differs from those already described, in that contrasting calcrete cements occur in upper and lower sections of the exposure. Much of the profile of calcrete N5 is very similar to that of profile S3, being

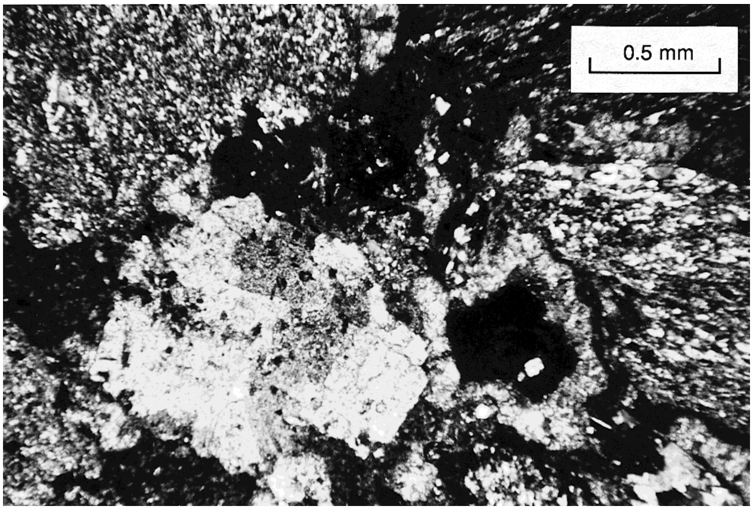

Figure 13. Petrographic thin section of calcrete sample TAB 96/12/3 from Profile S6b, showing schist fragments cemented by sparite with micrite and microsparite lining void spaces (cross-polarized light)

dominated by microcrystalline or micritic calcite, the slightly larger calcite crystals tending to occur closer to void spaces. The profile shows little variability except in its uppermost sections where concentric growth structures and glaebules occur, giving it an appearance similar to profiles N2, S2, N4 and S4. The glaebular or nodular structures are surrounded by a microcrystalline calcite cement, suggesting that nodules formed and were subsequently cemented together. Bulk chemical analysis of samples indicates that CaO content is highest at the top of the profile and generally stable for the rest of the profile, with associated decline in other constituents mirroring this variability (Table V). The high CaO content occurs in a calcrete with a relatively high cement to host material ratio, suggesting considerable displacement during calcretization. Such a relatively high level of displacement may indicate an abundant carbonate supply.

MODES OF CALCRETE GENESIS

Calcretes arising from two different mechanisms of formation – pedogenic and groundwater calcretization – appear to be present within the Tabernas Basin, with one profile containing evidence for both modes of development. The term ‘groundwater calcrete’ is considered synonymous with other frequently used terminologies such as phreatic, valley and channel calcretes for the purposes of this discussion (Wright and Tucker, 1991).

Pedogenic calcrete profiles

Calcrete profiles N2 and S2 and, to a lesser degree of development, N4 and S4 exhibit features characteristic of pedogenic calcretes (e.g. Aristarain, 1970; Watts, 1980; Machette, 1985; Blümel, 1991). In the more strongly developed profiles, N2 and S2, upper zones of the profile are highly indurated with the development of laminar surface layers. CaO concentration decreases down both profiles, as does the degree of cementation, with both profiles having a diffuse lower boundary. Both profiles are Stage IV calcretes according to the standard pedogenic calcrete classification schemes of Gile *et al*. (1966) and Machette (1985). Micromorphological examination shows that the calcretes are dominated by fine-grained micritic calcite and glaebules or nodular structures, both consistent with a pedogenic origin (Wright and Tucker, 1991). Profiles N4 and S4 (both Stage II+ calcretes) on a lower, younger palaeosurface show similar profile trends with less carbonate accumulation within the profile. In both sample locations, the degree of induration decreases down the profile reflecting a decrease in the amount of calcium carbonate cement and suggesting a vertical translocation and net accumulation of carbonate during their formation (Gile *et al*., 1966). Pedogenic carbonate accumulation leading to calcrete formation can only take place in environments where carbonates are not leached from the profile and

where there are prolonged and severe soil moisture deficits resulting from potential evaporation far exceeding annual precipitation. This would suggest that during the past, when pedogenic carbonate was accumulating, the Tabernas area experienced sufficiently low levels of rainfall to prevent carbonate removal from profiles. Similar pedogenic calcretes have been reported from other areas of southeast Spain beyond the Tabernas Basin, including parts of Murcia and Alicante provinces (e.g. Blümel, 1981, 1982). Calcrete profiles up to 3 m thick in the upper sections of alluvial deposits have additionally been described in the central Ebro Basin (Sancho *et al*., 1992), the Duero and Tajo Basins (Rodas *et al*., 1994), and the Sepúlveda–Ayllón Basin (Armenteros *et al*., 1995).

Groundwater calcrete profiles

In contrast to the distinctly pedogenic calcretes, sample profiles N1, N3, N6, S1, S3, S6a and S6b show a number of features more consistent with an origin as a groundwater calcrete. It appears most likely that calcretes formed as a result of cementation following the lateral transfer of carbonate-rich solutions through gravel parent materials, either in confined bedrock channels or above relatively impermeable planated bedrock. Studies of groundwater calcretes (e.g. Mann and Horwitz, 1979; Arakel and McConchie, 1982; Arakel, 1986; Wright and Tucker, 1991; Nash *et al*., 1994; Watson and Nash, 1997; Nash, 1997) suggest that calcretes formed in a phreatic setting do not develop mature profiles where carbonate decreases down-profile, but tend to be brecciated or massive in character. Wright and Tucker (1991) also suggest that, in general, thicker horizons are likely to be present in groundwater calcretes when compared to pedogenic varieties. Profiles N1, N3, S1 and S3 on the two extensive upper palaeosurfaces in the Tabernas Basin are typically 3 m thick, reaching maximum thicknesses of up to 6 m, whilst the deepest pedogenic calcrete profiles (N2 and S2) appear to be no more than 2 m thick. The most convincing evidence for a groundwater origin is the close association of calcretes N6, S6a and S6b with valley floors and bedrock channels. In situations where calcretes have developed within channel fills it is almost certain that the channel acted as a conduit for the movement of carbonate-rich solutions. Calcretes N1, N3, S1 and S3 are likely to have developed in a similar way, with the relatively impermeable bedrock underlying the schist gravels acting as a barrier to downward water migration. This argument is further supported by the localized thickening of the calcrete horizons in the vicinity of the gravel-infilled bedrock channels within the N3 calcrete to the west of the Rambla del Búho.

Some profile characteristics do not appear immediately to be consistent with calcretization in a groundwater environment. The laminar crusts present on the upper surfaces of many profiles are similar to crusts developed in superficial settings (Carlisle, 1983) on the top of pedogenic calcretes. The processes leading to the development of surface laminar crusts are the subject of ongoing debate, with opinion divided as to whether they form as a result of organic or inorganic processes (see Rabenhorst *et al*. (1991) for a summary). Formation by organic processes would tend to suggest a near-surface origin whilst inorganic accumulation could, in theory, occur at any depth as a result of percolating carbonate-rich waters becoming perched above an indurated calcrete horizon (Gile *et al*., 1966). There are, however, cases where laminar crusts have developed at depths of more than 3 m in the capillary fringe zone on top of groundwater calcretes, associated with the occurrence of phreatophytic plants (e.g. Semeniuk and Meagher, 1981).

The micromorphological evidence for a groundwater origin is more difficult to interpret. Wright and Tucker (1991) observe that groundwater calcretes typically have a micritic and densely crystalline cement but that the pore size range of the host sediment may be important in determining fabric characteristics. Raghavan and Coury (1987) have suggested that sparry calcites in Quaternary deposits in the Thar Desert, India, have precipitated from raised groundwaters during wetter 'pluvial' phases whilst more finely crystalline calcites reflect pedogenic processes under semi-arid or arid conditions. Whilst there is some variability, the fabrics of calcretes N1, N3, N6, S1, S3, S6a and S6b are distinctly different to the pedogenic types, being dominated by relatively simple sparite cements which infill pore spaces between gravels.

Combined groundwater and pedogenic calcrete profiles

Profile N5, developed within a thin alluvial fan over bedrock adjacent to the Rambla del Búho, shows a different combination of characteristics from the calcretes of the two major groups described above. The carbonate content decreases markedly in the upper metre of the profile from 44 per cent to 21 per cent, and the

profile has the highest carbonate content in the uppermost layer of all the calcretes described from the basin. The lower part of the profile has a uniform cement, with micrite adjacent to grains and microcrystalline calcite infilling voids. In this respect the profile is similar to many of the calcretes suggested to have developed through inputs of groundwater carbonate. There are, however, glaebules and concentric growth structures present in the uppermost section of the profile which appear similar to other pedogenic calcretes. On the basis of geochemical and micromorphological properties it would appear most likely that this calcrete has formed by a combination of groundwater and pedogenic calcretization close to the capillary fringe. As noted above, the relatively high degree of grain displacement in the uppermost sections of the profile suggests high inputs of carbonate reflecting the combination of calcretization processes.

DISCUSSION

On the basis of the calcrete properties and origins outlined above there appear to be two key questions regarding the development of calcretes within the Tabernas Basin. The first of these concerns the mechanisms required for the development of a pair of pedogenic and groundwater calcretes within the same gravel profile. Linked to this point, it is also important to determine what the presence of calcretes at a variety of positions within the landscape can tell us about basin development. These questions will now be considered.

Mechanisms for the development of paired calcrete profiles

These are two possible models for the development of the paired calcretes upon the two higher palaeosurfaces in the Tabernas Basin. The first is that accretion of the gravel sediments occurred upon a planated bedrock surface, and that at some point after gravel emplacement the two different mechanisms of calcretization were initiated. Groundwater calcretization appears to have occurred at the base of the gravel unit with the formation of a pedogenic calcrete at the top of the sequence. In this model, accumulation of the near-surface pedogenic calcretes would continue until a soil cover was lost from the upper land surface as a result of decreasing permeability in the calcrete horizon. After this point, the calcrete profile may undergo modification due to case hardening, secondary brecciation and recementation, but there would be little further addition of carbonate to the profile with the exception of minor inputs to laminar crusts from sheetflow. Formation of the basal groundwater calcretes, on the other hand, would continue until a period of landscape uplift and/or fluvial incision took place. At this stage, groundwater calcrete formation would cease or be substantially curtailed as a result of a lowering of the basin water table, unless a local or perched water table were present to allow further inputs of carbonate-rich groundwater.

A second model might suggest that groundwater calcretization of the basal sediments occurred contemporaneously with sediment accretion in the basin, with the upper surface of the groundwater calcrete representing a break in sedimentation. Once formed, the groundwater calcrete would have to be buried by an incursion of alluvial fan or fluvial gravels, with a pedogenic calcrete subsequently forming at the top of the gravel sequence.

The identification of the most likely model of paired calcrete development is not without problems, but a number of observations can be made. One of the most important controls on calcrete development within the Tabernas Basin is the presence of relatively impermeable bedrock directly beneath the host gravels. The extensive planated bedrock surfaces upon which the upper and lower paired calcrete units have developed are cut across fine-grained Neogene sedimentary bedrock. The lower, more spatially confined calcretes within the basin are also underlain by similar impermeable bedrock. The effect of these erosion surfaces or channels is to perch a water table within the overlying gravel deposits. Observations from Australia and Southern Africa (e.g. Carlisle, 1980, 1983) have demonstrated calcrete formation at considerable depth within sedimentary profiles and the formation of groundwater calcretes is not necessarily confined to near-surface zones – deposition can occur at depth within the capillary fringe of the phreatic zone.

Whilst the presence of a laminar crust on top of the groundwater calcrete units could be interpreted to suggest that these calcretes formed relatively close to the surface, the fact that there does not appear to be any significant change in particle size between the calcrete host material and overlying sediment (suggesting continuous sedimentation) supports the argument for formation at depth. Given that groundwater calcretes can form at

considerable depth, it is most likely that groundwater calcretization was initiated in basal gravels in the Tabernas Basin at or around the same time as pedogenic calcretes were forming at the surface. The nature of Profile N5, containing micromorphological characteristics typical of pedogenic calcretes in its upper section which merge downwards into a fabric more closely similar to other groundwater calcretes, supports this view. In this profile, which developed in a thin veneer of gravels, it would appear that the local water table was sufficiently high for groundwater calcretization to take place at or around the same time as pedogenic processes were forming a surface calcrete. The presence of microsparite cementing calcrete nodules suggests that a pedogenic calcrete was extending downwards into the gravel profile at the same time as a groundwater calcrete was forming from the base of the profile.

The paired calcretes described in this paper are not unique in the geomorphological literature. In the Ksabi Basin in Morocco, Kaemmerer and Revel (1991) have identified profiles similar to those of the upper palaeosurfaces of the Tabernas Basin. Two calcretes are present in the Ksabi Basin, developed within approximately 12 m of coarse-grained alluvial deposits. The upper pedogenic calcrete is 1·4 m thick and dominated by a micritic calcite fabric. This is separated by 60 cm of non-cemented gravel from a lower calcrete of 10 m thickness, which is uniform in character and dominated by sparite or microspar calcite cement. Kaemmerer and Revel (1991) make a distinction between calcretes which they identify as pedogenic surface phenomena and *encroutement de nappe* which are the equivalent of groundwater calcretes. In the Tabernas Basin, the microfabric of the pedogenic calcrete profiles is dominated by micrite, with glaebules and concentric growth structures present in all profiles. In contrast, the calcretes suggested to have developed by groundwater calcretization have a sparite cement with concentric layers of calcite lining pores. These microfabrics show more variability than the groundwater calcretes described by Kaemmerer and Revel (1991), but in other respects appear to be similar. It may be that the calcretes in the Tabernas Basin formed in a more near-surface environment and were subsequently buried, but the micromorphological evidence is equivocal and further weathering studies are necessary.

Geomorphic significance of calcrete development

The fact that both groundwater and pedogenic calcretes occur in the Tabernas Basin, often in the same profile, has a number of implications for understanding basin development. The extent of calcrete formation appears to have been controlled by periods of uplift and stability. Planation of bedrock, leading to the creation of extensive palaeosurfaces, is likely to have taken place under relatively stable conditions. This period of stability was followed by periods of gravel deposition possibly representing increased sediment production in the catchment, increased sediment supply (due to basin instability) or increased runoff. Calcretization is likely to have taken place under stable basin conditions, with formation of groundwater calcretes terminated by basin uplift or incision due to increased fluvial activity.

Basin incision may have been initiated following a period of uplift, but may also be due to a change in regional climate. For example, calcrete exposures in the western part of the Basin, to the north of the Rambla de Tabernas and adjacent to the Grenada–Almería road (37° 02′ N, 002° 27′ W), provide conclusive evidence for tectonic activity subsequent to calcrete development. The uppermost calcretes in this region, equivalent to units N1 and N2, are disrupted by faulting, with a downthrow in excess of 3 m. Owing to relatively limited exposure of the fault zone in this region it is not possible to ascertain the precise orientation of the fault, but it appears to be normal fault aligned approximately north–south. Such tectonic movements are likely to have been a major influence upon patterns of sustained or pulsed incision within the Basin, although local base levels may be important at the local scale. Conversely, phases of aggradation within the Basin may only locally be related to tectonic activity as they are also influenced by sediment supply factors which are, at least in part, climatically controlled. This would suggest that whilst the sequence of calcretized land surfaces within the Tabernas Basin is predominantly determined by tectonic movement, there is also likely to be at least some climatic influence upon aggradation and incision.

In addition to allowing an assessment of periods of stability and instability in the Tabernas Basin, a comparison of the different calcrete units may also indicate the relative speed of calcrete formation by pedogenic and groundwater mechanisms. The differing degree of calcretization of the surface and basal gravels (e.g. Profiles N2 and N1, or N4 and N3) points to a substantial difference in accumulation rates in pedogenic and

Table VII. Bulk chemistry of alluvial fan gravels from the upper gravel unit within the Tabernas Basin separating calcretes N1 and N2 (sample location 37° 02′ N, 002° 27′ W). Analysis by XRF

	Bulk chemical data (% composition)							
Sample number	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Other	LOI (%)	Total
TAB96 Gravel 1	53·77	23·85	7·45	1·65	0·48	6·75	5·67	93·95
TAB96 Gravel 1 (duplicate)	53·45	23·99	7·49	1·71	0·47	6·82	5·67	93·91
TAB96 Gravel 2	53·40	23·81	7·40	1·63	0·47	6·83	5·69	93·54
TAB96 Gravel 2 (duplicate)	53·38	23·88	7·40	1·67	0·48	6·66	5·69	93·47

groundwater settings. This can be seen by reference to the bulk chemistry of representative samples of the uncemented gravels from the gravel unit between calcretes N1 and N2 (Table VII). The basal groundwater calcretes are much thicker than the overlying pedogenic varieties, indicating that rates of carbonate accumulation may be relatively rapid in groundwater situations. Comparatively little is known about rates of formation of groundwater calcretes, although it has been suggested that their development may be less limited by carbonate supply than pedogenic varieties (Rabenhorst *et al*., 1991; Wright and Tucker, 1991). The low levels of carbonate within the host schist-rich gravels would almost certainly preclude the direct development of a carbonate cement through weathering of these materials. The carbonate needed for groundwater calcrete formation is therefore most likely to have been supplied by the weathering and dissolution of carbonate-rich Tortonian and Messinian bedrock within the basin. Pedogenic calcretes, in contrast, are separated from the underlying carbonate-rich bedrock by several metres of schist-dominated gravel, making the most likely carbonate sources either dust or, more probably, surface wash inputs. Profile N5, a well developed calcrete in a low position in the Rambla del Búho, which appears to have developed in shallow gravels but with a groundwater influence, suggests that calcrete formation may be rapid under certain circumstances in a near-surface environment.

CONCLUSION

This study has identified calcretes with different modes of origin in a variety of geomorphological settings within the Tabernas Basin. Calcretes occur either as cemented units preserving planated former land surfaces or are confined to the floors and flanks of incised drainage channels. In the Tabernas Basin, two former land surfaces have been buried by a veneer of alluvial fan or fluvial gravels. Calcretes of pedogenic origin occur in the upper surfaces of these gravel deposits. The extent of calcrete cementation is greatest in the upper parts of the gravels covering the highest of the two former land surfaces. The carbonate source is uncertain but may, in part, result from dust inputs or surface wash. At the base of these gravel sequences, calcretes occur which appear similar to groundwater calcretes described elsewhere. The carbonate which cements these gravels is probably derived from the Neogene sediments which infill the Tabernas Basin. Calcretes of a similar origin also occur within bedrock channels at lower levels within the basin. A thin calcrete formed in a small alluvial fan in the Rambla del Búho appears to be in part of groundwater origin but has formed in a near-surface position and exhibits features typical of pedogenic calcretes in its uppermost sections.

In deep gravel sequences, groundwater and pedogenic calcretes may be separable on morphological grounds but in shallower deposits the possibility of groundwater inputs to pedogenic calcretes needs to be considered, and hybrid forms of calcrete may exist. In the Tabernas Basin, calcretes play an important role in the stabilization of former land surfaces. On the highest palaeosurface this is a combined effect of an upper pedogenic calcrete and a lower groundwater calcrete unit. On the lower palaeosurface the upper pedogenic calcrete is relatively weakly developed and the major landscape control relates to the basal calcrete unit. Parallels exist between this situation and that described from Morocco by Kaemmerer and Revel (1991) where thick groundwater calcretes appear to be the dominant caprocks in the landscape.

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